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Modelling of Bacterial Growth with Shifts in Temperature Using Automated Methods with *Listeria monocytogenes* and *Pseudomonas aeruginosa* as examples

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Abstract

Time to detection (TTD) measurements using turbidometry allow a straightforward method for the measurement of bacterial growth rates under isothermal conditions. Growth rate measurements were carried out for *Listeria monocytogenes* at 25, 30 and 37^{o}C and for *Pseudomonas aeruginosa* over the temperature range 25 to 45^{o}C. The classical three- parameter logistic model was rearranged to provide the theoretical foundation for the observed TTD. A model was subsequently developed for the analysis of TTD data from non-isothermal studies based on the Malthusian approximation of the logistic model. The model was able to predict the TTD for cultures of *L. monocytogenes* or *P. aeruginosa* undergoing simple temperature shunts (e.g. 25 to 37^{o}C and vice versa), and for a multiple temperature shunt for *L. monocytogenes* (25-37-25-37^{o}C and 37-25-37-25^{o}C) over a period of 24 h. In no case did a temperature shunt induce a lag.

1 Introduction

The measurement of microbial growth rate especially its temperature dependency, is of fundamental importance in food microbiology. For many food pathogens growth above 25 and below 45^{o}C is usually rapid with an optimum around 37^{o}C. Below 5^{o}C only a few microorganisms, either spoilage organisms (e.g. *Pseudomonas aeruginosa*) or pathogenic (e.g. *Listeria monocytogenes*) have growth rates that would give rise to concern. This has been shown, for example, by Thomas and O'Bierne (2000) on the temperature abuse of vegetables.

Within the literature, several studies have looked at the effect of non-isothermal conditions on microbial growth using established modeling methods (e.g. Baranyi *et al*., 1995; Bovill *et al*., 2000; Dalgaard *et al*., 2002; Giannakourou *et al*., 2005; Koutsoumanis, 2001; Koutsoumanis *et al*., 2006; Li and Torres, 1993; Taoukis *et al*., 1999; Zwietering *et al.,* 1994). One aim of many of these studies was to test the suitability of using models based on growth data obtained isothermally to predict growth under non-isothermal conditions. Zwietering *et al*., (1994) concluded that, within the exponential phase, the hypothesis of no lag occurrence was accepted statistically in more than 70% of their experiments for *Lactobacillus plantarum*, however, within the lag phase, the hypothesis of additional lag occurrence was accepted statistically in more than 90% of their experiments.

Corradini and Peleg (2005) have eloquently questioned the reasoning and conclusions being drawn from the use of the empirical standard primary and secondary models used to interpret and predict data from isothermal and fluctuating temperature studies. They suggest abandoning specific formats and using, instead, a generalized scheme for both primary and secondary modeling, "in the absence of a decisively superior theoretical model… [ad hoc empirical models] have the advantage of being simpler mathematically and free of assumptions that require independent verification".

Automated techniques such as turbidometry tend to come under fire from traditional microbiologists since they cannot directly reproduce the standard microbial growth curve, which the multitude of primary models are fitted to (Augustin *et al.,* 1999; Dalgaard *et al.,* 1994; McClure *et al.,* 1993), yet their very persistence reflects their ease of use, the high quantity and quality of the data obtained and the large savings in consumable costs over that of the traditional (plate-count) methods. We have recently shown that the modified Gompertz and modified logistic models are at odds with the observed time to detection data (TTD) obtained using turbidometry (Mytilinaios *et al.,* 2011). The classic logistic model (and by default the Baranyi equation) were the only models used that were able to reconstruct the observed TTD data. Herein we further examine the application of the basic logistic model to microbial growth data (obtained as TTD) and use small temperature shifts (or shunts), to examine their effect on the growth rates of *L. monocytogenes* and *P. aeruginosa*. The temperatures used in this study (25^{o}C and greater) were chosen to develop the model prior to low temperature studies.

2 Methods

2.1 CULTURE PREPARATION:

Pseudomonas aeruginosa (ATCC 15442, isolated from bottled water) or *Listeria monocytogenes* (L-252, an industrial isolate provided by Nestlé Research Centre, Lausanne– obtained from contaminated meat terrine (paté) was grown overnight in conical flasks containing 80 ml Tryptone Soya Broth, TSB (Oxoid CM 129) shaking continuously at 30°C. The cells were harvested, centrifuged (510g, 10 minutes) and the resulting cell pellets resuspended in 2 ml TSB. The inoculum was standardised by diluting to an approximate OD=0.5 at 600 nm giving approximately $2x10^9$ cfu/ml. This standardised culture was subject to either ten decimal or ten half-fold dilutions in TSB.

2.2 PREPARATION OF MICRO-ARRAY PLATES

Each well in the Bioscreen (Labsystems, Helsinki, Finldand) micro-titre plates was filled as follows: all wells except column 10 received 200µl of growth broth (TSB). The wells of column 10 were given 400µl of the appropriate serial dilutions (decimal or half fold), with the highest inoculum (the zero dilution) in well 100. Using a multi-pipette, 200µl were removed from each well of column 10 and transferred into the wells of column 9, mixed by repeated syringing, and then 200µl were removed (using new tips) from the wells of column 9 and transferred to column 8 etc. This was repeated across the plate discarding 200µl after the final mixing in column 1.

From the -5 and -6 decimal dilutions, 0.1 ml of each was transferred and spread onto previously prepared tryptone soya agar (TSA) plates in triplicate and incubated at 30˚C for 2 days. Plates with <300 cfu were counted and the approximate log number of the initial (zero dilution) culture calculated.

For the study of the growth rates, identical plates were placed in different Bioscreens set at particular temperatures, chosen in the range from 25 to 45^{o}C. After a given time of incubation the plates were swapped between the machines, without changing the running of the machines. Typical experiments lasted 1 to 2 days. The optical density of the wells was read at 600nm every ten mins.

One particular effect was noted with Bioscreen data when the plates were removed from a higher incubation temperature to a lower (but not vice-versa); a kink in the OD/time plot due to the temporary presence of condensation on the underneath of the lid of the Bioscreen plates. In general the condensation took between 30 to 50 mins to evaporate. Thus, TTD which met the OD criterion (**see below**) were censored during the first 30 to 50 mins after the transfer.

2.3 DATA ANALYSIS

From the resulting Bioscreen OD/time data, the background OD due to the media was removed from each. A TTD criterion of OD = 0.2 was then used on the background corrected data: TTD were found using linear interpolation between OD/time values which straddled the OD = 0.2 value. Wells with an expected number of cells below approximately 50 per well were censored from the analysis. Below this value the variance in the data increases due to the random process of organism selection (Standaert et al 2005).

2.4 MODEL DEVELOPMENT

Theoretical Background: From the classical logistic equation

$$N = \frac{M}{1+\left(\frac{M}{N_0}-1\right)e^{-\mu t}} \qquad (1)$$

where μ is the specific growth rate (with units of 1/time) and M is the maximum population density (also known as the carrying capacity, cfu/ml), the time taken (TTD) to reach a specific population level (N) from a given initial value (N_0, cfu/ml) is given by

$$TTD = -\frac{1}{\mu}\ln N_0 + \frac{1}{\mu}\ln\left(\frac{N(M-N_0)}{M-N}\right) \quad (2)$$

The TTD is defined as the time to reach a given detection threshold (e.g. an optical density of 0.2) for which N_d is the equivalent microbial numbers per ml. If the assumption that $M>>N_0$ is made then this can be approximated by

$$TTD = -\frac{1}{\mu}\ln N_0 + \frac{1}{\mu}\ln\left\{\frac{N_d M}{M-N_d}\right\} \quad (3)$$

When N_0 =1, the TTD is given by the right hand expression of eq.3, if $M>>N_d$ then this can be approximated by N_d/μ. Hence, a plot of the initial inoculum against the TTD will give a gradient equal to the negative reciprocal of the growth rate, the TTD intercept at N_0 = 1, is the time taken for one organism to reach the TTD criterion. This expression can be considered as the basis of the methodology of Cuppers and Smelt (1993) described below. In the presence of a lag equation 2 can be supplemented with a lag term, else the Baranyi equation can be used, but the required parameters have to be found using a more involved numerical technique.

Geometric or Malthusian model

For a given set of environmental conditions a plot of the log of the initial inoculum size against the TTD gives a straight line relationship with gradient equal to the reciprocal of the specific growth rate (Cuppers and Smelt 1993). In the absence of a lag the line will intersect the log initial inoculum axis at the detection value for the given OD criterion used.

If two microtitre plates each containing identically prepared multiple inocula are incubated at different temperatures then each inoculum will grow at a rate dictated by the temperature and

media conditions. The difference between the two plates will be governed only by the differential effect of the temperature. For each initial inoculum the TTD can be given by

$$TTD = g(\log I - \log I_D) \qquad (4)$$

Where log I is the log of the initial inoculum used, log I_D is the log of the detection number and g is the gradient of the TTD, log$I$ plot.

We hypothesise that if at time t_i the incubation temperature is changed then, whether in the absence or not of an induced lag, the growth rate will increase or decrease to meet the demands of the new incubation temperature (Figure 1). Incubation at temperature T_0 gives an observed gradient of g_0; at time t_i, the temperature is changed to T_1 (where, in this case, T_0 is more optimal for growth than T_1), the gradient changes to g_1, commensurate with the new incubation temperature.

From simple geometrical arguments it can be shown that the TTD for multiple changes of temperature is given by equation 5.

For time: $t_i < t < t_{i+1}$, for i= 0,1,2,.., where $t_0 = 0$,

$$TTD = t_i + g_i\left(\log I - \log I_D - \sum_{j=0}^{j=i}\left(\frac{t_j - t_{j-1}}{g_{j-1}}\right)\right) \qquad (5)$$

For example,

For i = 0 $\quad TTD = g_0(\log I - \log I_D)$

For i = 1, $\quad TTD = t_1 + g_1\left(\log I - \log I_D - \frac{t_1}{g_0}\right)$

For i = 2, $\quad TTD = t_2 + g_2\left(\log I - \log I_D - \left\{\left(\frac{t_2 - t_1}{g_1}\right) + \left(\frac{t_1 - t_0}{g_0}\right)\right\}\right)$

If lags are induced at t_i, then the expression for t_i can be replaced by $t_i = t_i + \lambda_i$. For a given experiment the values of t_i are fixed.

Since the models are simple linear models, the majority of the modelling was carried out using Excel (Microsoft, Reading UK) with the data analysis add-in package.

3 Results

3.1 ISO-THERMAL STUDIES

From plots of the optical density/time curves for multiple inocula of *L. monocytogenes 252* (from 1.2 x10^9 cfu/ml to 1x10^2 cfu/ml) incubated at 25, 30 and 37^{o}C it was evident that there was no lag present; analyses of the curves for inocula which had initial OD greater than the background showed immediate growth. A plot of the TTD defined as the time to reach an OD = 0.2 against the log of the initial inocula gave a straight line plots. From the reciprocal of the gradients of the fitted lines the growth rates were obtained; the intercept on the TTD axis was the time taken for one organism to reach the detection criterion (Table 1). For zero lag the line cuts the log initial inoculum axis at the log inoculum size equivalent to the optical density of the TTD criterion. The microbial density obtained from direct plating of an OD = 0.2 at 600nm in the Bioscreen was equivalent to 9.09 $\log_{10}$ cfu ml^{-1} (95% CI: 8.97 – 9.21).

P. aeruginosa was analysed in a similar manner but over a wider range of temperatures (Table 1). An optimum growth temperature of approximately 39^{o}C was apparent; with a specific growth rate of 1.51 /h. None of the studies conducted showed the presence of a lag. The fitted lines cut the log inoculum axis at the detection number threshold value (data not shown). The data shown for growth at 37^{o}C have approximately constant variance until the initial inoculum level is less than approximately 50 cfu/ml. Below this level the variance increases. To preclude the need for weighted regression, data below this threshold were censored in the regression fits.

3.2 NON-ISOTHERMAL STUDIES

Two temperature shunt studies

L. monocytogenes: Figure 2 shows the observed optical density curves from a Bioscreen incubating at 25^{o}C for an experiment with *L. monocytogenes* 252, in which one plate was incubated at 25^{o}C, removed after 500 mins and replaced with one which had been initially

incubated in a separate Bioscreen at 37oC. Figure 3 shows a close up of the discontinuity in the OD curves for several selected initial inocula.

Figure 4 shows the observed TTD data from two plates incubated initially for 400 mins at 25 and 37^{o}C and then transferred to the Bioscreens incubating at 37 and 25^{o}C respectively; Figure 5 shows a similar experiment done with incubation at 30 and 37^{o}C. The gradients of the lines are given in Table 2 and in each case the gradients obtained follow approximately those found from the isothermal data (Table1). Further, there were no indications of induced lags after the plates were exchanged. A lag would result in a vertical gap between the two rates (see Figure 1).

P. aeruginosa: Table 3 gives the observed gradients and intercepts for a temperature shunt of 25 to 39^{o}C and vice versa and also for 34 and 39^{o}C. Figure 6 shows the data obtained from the Bioscreen incubating at 37^{o}C for the 37 to 30^{o}C shunt. The initial incubation at 37^{o}C gave a gradient of -95.2 (-99.90 to -90.50 : 95% CI) mins/$\log_{10}$ cfu/ml; the gradient of the plate initially incubated at 30^{o}C but placed into the 37^{o}C incubator after 300mins was -92.96 (-96.9 to -89.02 : 95% CI) mins/$\log_{10}$ cfu/ml. The horizontal separation of the two was calculated as 0.887 $\log_{10}$cfu/ml., i.e. the plate incubated at 30^{o}C was growth retarded relative to growth at 37^{o}C by just less than 1 log cfu/ml after 300 mins of incubation.

Multiple Temperature Shunts: Figure 7 shows the observed times to detection for multiple initial inocula of *L. monocytogenes* undergoing either a 37-25-37-25^{O}C or a 25-37-25-37^{o}C temperature incubation sequence, changing temperatures after 360, 500 and 900 mins. The observed gradients were -107.9, -179.3,-105.2,-NA (no data available) for the 37-25-37-25^{o}C sequence and -193.5,-104.7,-172.6,-110.0 for the 25-37-25-37^{o}C sequences respectively. Superimposed on Figure 7 are the predicted values from the Geometric model, the TTD predictions of which are based on the growth rate data given in Table 1.

Modelling

The Geometric model (Eq. 5)can be either used to predict the outcome of hypothetical experiments, as was done for the multiple temperature shunt with *Listeria* shown in Figure 7, or can be used to fit the observed data by minimising the sum of squares of the errors. Another method of using the predictive capacity of the model is to predict the TTD observed from a single Bioscreen incubating at a given temperature, when identical plates are moved in or out of the machine. Figure 8 shows a prediction of the pattern of TTD/log initial inocula from the single Bioscreen incubating at 37^{o}C. Using the growth rates described in Table 1, in 360 mins the model predicts that 3.27 logs of growth will occur in this plate, whereas the other plate incubating in the other machine at 25^{o}C will increase by only 1.97 logs. When the latter plate is placed in the machine at 37^{o}C, if there are no lags then over the next 240 mins there will be further increase of 2.18 logs in this plate. By calculating the log increase in the numbers of *L. monocytogenes* at 37^{o}C and that incubated at 25^{o}C and then subsequently placed at 37^{o}C, the pattern shown in Figure 8 was obtained. The observed data are overlain on the predicted lines.

4 Discussion

The simple, classical three-parameter logistic model can model the TTD data obtained from turbidometric experiments using multiple initial inocula incubated iso-thermally. In all cases studied, no lags were observed either from the OD/incubation time plots or from the plotted or modelled data. Plots of the log initial inoculum against the TTD cut the log I_0 axis at 9.22 $\log_{10}$ cfu/ml (95% CI 9.05 – 9.4 $\log_{10}$ cfu/ml) and at 9.15 $\log_{10}$ cfu/ml (95% CI 8.9 – 9.4) for *L. monocytogenes* and *P. aeruginosa,* respectively. The detection number (N_d) for each species was confirmed by plate counting and from calibration curves of OD against microbial numbers. In the presence of a lag, the plot would fail to cross the axis at the N_d, and a vertical separation equal to the lag between the x-axis and the TTD of the N_d would be present.

The linear approximation (eq.4) to the logistic expression (eq.2) assumes that $M >> N_d \geq N_0$; when $N_0 = N_d$, TTD = 0. If $M < 10N_d$ then curvature of the observed TTD occurs, if $M < 3N_d$ then this curvature is substantial and the mismatch between eq.4 and eq.2 becomes significant. In all the cases studied here, $M > 10N_d$ and this curvature was not observed. If the detection threshold is increased, e.g. use of a higher OD threshold, then a curvature is observed (data not shown). Conversely, lowering the threshold would reduce any observed curvature. Equation 4 does not require the estimation of the maximum population density (MPD), and in the absence of a lag is a two parameter model. Rearranging eq. 4 results in the Malthusian approximation of biological growth – i.e. growth without limit. The value of M is, however, used in the full form of the logistic model. M can be obtained through plate count, from dilutions of the MPD culture to produce a calibration curve using OD or from using the phenomenon of curvature discussed above.

When a temperature shunt was applied to growing bacteria, the cultures reduced or increased their growth rate commensurate with the incubation temperature. When cultures were shunted from a lower temperature to a higher temperature there was no evidence of an induced lag and

growth continued at the rate dictated by the new temperature. These observations are in accordance with the general conclusion of Zwietering *et al*., (1994). When cultures were shunted from a higher to a lower temperature condensation on the inside of the plate lid occurred and this led to unusable data for a period after the shunt (the period depended on the temperature difference). From the observed, fitted and predicted data it can be concluded that no induction of lag occurred when moving from the higher to the lower temperatures used: the intercept of the regression lines for each temperature coincided at the time of the temperature shunt, something that, if lags were present, would not occur (e.g. Figure 7).

The traditional method of examining growth using plates can be considered to be a repeated measures experiment following the growth of an initial inoculum with time, whereas the method used here is a multiple inoculum experiment with a single time measurement (the TTD) per inoculum. These methods should be considered not as complementary but methods describing the same phenomenon of microbial growth, done in a different fashion. However, the models used to extract the growth rate data from the two methods are not consistent: the modified Gompertz and modified logistic model cannot reproduce the observed TTD data (Mytilinaios *et al.,* 2011). This has implications when such models are used to examine data obtained from turbidimetry.

Conclusion: Using micro-titre plates with multiple inocula allows the investigation of a wealth of phenomena - such as the temperature shifts investigated here. From our modest results, we conclude that for small temperature shifts within the ranges studied, for *L. monocytogenes* and *P. aeruginosa*, growth rates quickly change to the new environment without the induction of lags and that the logistic model is an adequate descriptor and theoretical model for TTD data obtained from turbidometry.

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Table 1. Isothermal Rate data from the TTD analysis of multiple initial inocula of *L. monocytogenes and P. aeruginosa*

Organism	Temp °C	- Gradient min/log_{10}l (95% CI)	SGR (/h)	Intercept min (95% CI)	r^2	Obs
Listeria monocytogenes	25	183.40 (185.94, 180.86)	0.753	1687.6 (1671.7, 1703.6)	0.993	153
	30	130.30 (131.90, 128.70)	1.060	1221.4 (1211.0, 1231.7)	0.994	153
	37	109.98 (110.85, 109.10)	1.256	999.22 (993.90, 1004.6)	0.997	160
Pseudomonas aeruginosa	25	202.24 (205.33,199.15)	0.683	1908.7 (1889.2, 1928.1)	0.991	161
	27	140.73 (143.54, 137.92)	0.982	1295.1 (1279.1, 1311.1)	0.984	157
	30	123.84 (125.24, 122.43)	1.116	1122.4 (1114.3, 1130.5)	0.994	154
	34	99.17 (100.80, 97.54)	1.393	883.05 (873.74, 892.34)	0.989	157
	35	96.04 (97.52, 94.57)	1.439	889.61 (880.60, 898.62)	0.991	149
	37	91.80 (92.86, 90.75)	1.505	846.13 (840.00, 852.27)	0.995	157
	39	91.38 (93.26, 89.49)	1.512	826.70 (818.78, 834.78)	0.987	122
	42	100.84 (102.67, 99.01)	1.370	923.14 (911.90, 934.37)	0.988	147
	45	125.81 (128.41, 123.21)	1.098	1137.8 (1121.7, 1153.9)	0.983	160

SGR is the specific growth rate

Table 2. Temperature shifts: Regression parameters from the observed TTD from multiple initial inocula of *Listeria monocytogenes 252* shunted from 25 to 37°C and 30 to 37°C and vice versa after a period of initial incubation.

		25 to 37°C					37 to 25°C			
		Coefficients	LCL	UCL	r^2 (obs)		Coefficients	LCL	UCL	r^2 (obs)
t < 400 mins	Intercept	1758.9	1645.7	1872.0	0.943	Intercept	972.97	954.82	991.12	0.984
	g0	-194.75	-209.15	-180.35	(47)	g0	-107.88	-110.46	-105.30	(112)
t > 400 mins	Intercept	1121.9	1110.1	1133.7	0.988	Intercept	1441.0	1418.5	1463.4	0.992
	g1	-104.25	-106.47	-102.02	(103)	g1	-198.8	-204.40	-193.21	(45)

		30 to 37°C					37 to 30°C			
		Coefficients	LCL	UCL	r^2 (obs)		Coefficients	LCL	UCL	r^2 (obs)
t < 410 mins	Intercept	1333.6	1302.5	1364.6	0.985	Intercept	983.14	975.06	991.23	0.997
	g0	-147.31	-151.55	-143.07	(72)	g0	-109.30	-110.48	-108.12	(108)
t > 410 mins	Intercept	1068.5	1057.7	1079.4	0.991	Intercept	1166.1	1144.5	1187.7	0.986
	g1	-106.60	-108.82	-104.38	(84)	g1	-145.56	-151.02	-140.10	(44)

Intercept, mins; go and g1, mins per $\log_{10}$ change in numbers; LCL,UCL: lower and upper 95% confidence values

Table 3. Temperature shifts: Regression parameters from the observed TTD from multiple initial inocula of *Pseudomonas aeruginosa* shunted from 25 to 39°C and 34 to 39°C, and vice versa after 300 minutes of incubation.

		25 to 39°C					39 to 25°C			
		Coefficients	LCL	UCL	r^2 (obs)		Coefficients	LCL	UCL	r^2 (obs)
t < 300 mins	Intercept	2081.9	1783.8	2380.0	0.91	Intercept	854.35	820.60	888.1	0.951
	g0	-228.26	-264.20	-192.33	(19)	g0	-91.89	-96.58	-87.21	(80)
t > 300 mins	Intercept	1035.8	1025.4	1046.1	0.987	Intercept	1639.5	1600.7	1678.2	0.972
	g1	-91.79	-93.57	-90.00	(140)	g1	-208.55	-216.8	-200.31	(75)

		34 to 39°C					39 to 34°C			
		Coefficients	LCL	UCL	r^2 (obs)		Coefficients	LCL	UCL	r^2 (obs)
t < 300 mins	Intercept	907.07	866.26	947.89	0.954	Intercept	811.66	832.49	854.58	0.980
	g0	-99.12	-104.81	-93.43	(61)	g0	-89.00	-91.96	-86.03	(75)
t > 300 mins	Intercept	868.04	855.48	880.59	0.982	Intercept	872.48	854.58	890.38	0.973
	g1	-92.64	-95.24	-90.02	(93)	g1	-100.47	-104.55	-93.39	(69)

Intercept, mins; go and g1, mins per $\log_{10}$ change in numbers; LCL,UCL: lower and upper 95% confidence values

Table 4. Observed regression parameters from the observed TTD from multiple initial inocula of *Listeria monocytogenes 252* shunted from 37, 25, 37,and 25^{0}C and concurrently from 25, 37, 25, and 37^{o}C.

Time (mins)	Temp (^{o}C)	Parameter	Estimate	LCI	UCI	r2 (obs)
		log Id	9.48	9.26	9.71	
<360	37	g0	-107.92	-108.36	-106.47	0.998(38)
<600	25	g1	-179.29	-188.04	-170.54	0.992 (17)
<900	37	g2	-104.62	-106	-103.25	0.998(52)
>900	25	g3	-	-	-	no obs

time	Temp	Parameter	Estimate	LCI	UCI	r2 (obs)
		log Id	9.58	7.98	11.52	
<360	25	g0	-193.5	-212.59	-174.4	0.981 (12)
<600	37	g1	-104.73	-106.54	-102.93	0.997(42)
<900	25	g2	-174.69	-189.12	-160.26	0.971 (21)
>900	37	g3	-109.52	-114.69	-104.35	0.984 (33)

$\log I_d$, $\log_{10}$ cfu/ml; g_i mins per $\log_{10}$ change in numbers

Figure 1.The geometrical basis for equation 5: for a given rate (g_0), over the time period T_x initial inocula between $\log I_D$ –$\log I_x$ will reach the detection threshold of log I_d. If at T_x the rate is changed (g_1) and there is no induction of lag, the TTD now follow the new rate. If a lag is induced a vertical separation at T_x equal to the time of lag will be present before growth recommences.

Figure 2. Optical density/incubation time curves for *L. monocytogenes* incubated at 25°C for 500 mins, subsequently removed and replaced with a similarly prepared plate incubated at 37°C for 500 mins. From left to right the $\log_{10}$ of the initial inoculum density is from 9.4 to a theoretical -2.26; carried out as a ten fold dilution sequence down and a half-fold dilution sequence across the microtitre plate.

Figure 3. An examination of the difference in the OD/time curves for 8 specific initial inocula of *L. monocytogenes* incubated at 25°C for 500 mins, subsequently removed and replaced with a similarly prepared plate incubated at 37°C for the first 500 mins (solid line : negative control; ■, 4.74; □, 5.34; ▲, 5.74; △, 6.04; ◆, 6.74; ◇, 6.94; ●, 7.04; ○, 7.34 $\log_{10}$cfu/ml).

Figure 4. Observed TTD data for *L. monocytogenes* incubating at 37 or 25°C with a temperature shunt to 25°C or 37°C (open circles and open squares respectively) after 400 mins incubation at the initial temperature. Solid lines are the fitted regression lines (Table 2).

Figure 5. Observed TTD data for *L. monocytogenes* incubating at 37 or 30°C with a temperature shunt to 30°C or 37°C (open circles and open squares respectively) after 410 mins incubation at the initial temperature. Solid lines are the fitted regression lines (Table 2).

Figure 6. Observed TTD data (symbols)for an initial plate of multiple inocula of *P. aeruginosa* incubating at 37°C for 300 mins, replaced by an identically filled plate after incubation at 30°C for 300 mins . The solid lines are the predicted TTD based on the data of Table 1 and the use of the logistic model to calculate the expected increase in numbers in both plates.

Figure 7. Observed TTD data for *L. monocytogenes* incubating at 37-25-37-25°C (open circles) or 25-37-25-37°C (open squares) with temperature shunts occurring at 360, 600 and 900 mins. The solid lines are the predicted values based on the data of Table 1, with Nd = 9.4.

Figure 8. Observed TTD data (symbols) and predicted data (solid line) from a single Bioscreen incubating at 37°C for multiple inocula of *L. monocytogenes* undergoing plate changes to and from another machine incubating at 25°C (see figure 7). The solid lines are the predicted TTD based on the data of Table 1 and the use of the logistic model to calculate the expected increase in numbers in both plates during the periods of incubations at 37 and 30°C. The parallel dashed lines are the linear regression fits to the observed data.

Figure 1

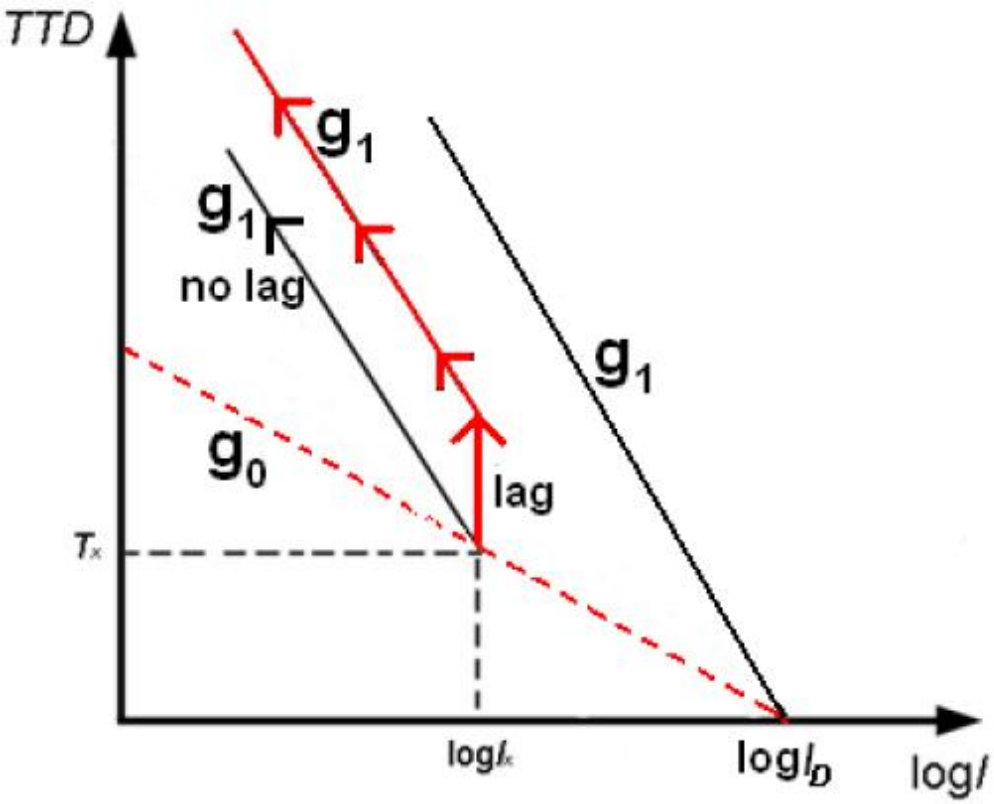


Figure 2

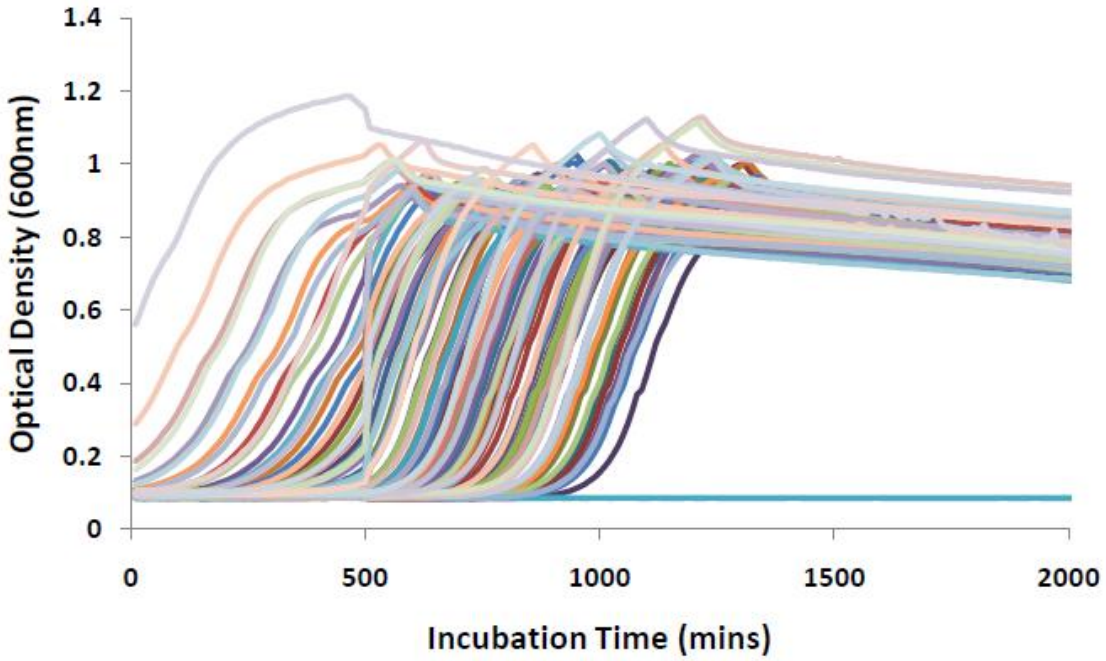


Figure 3.

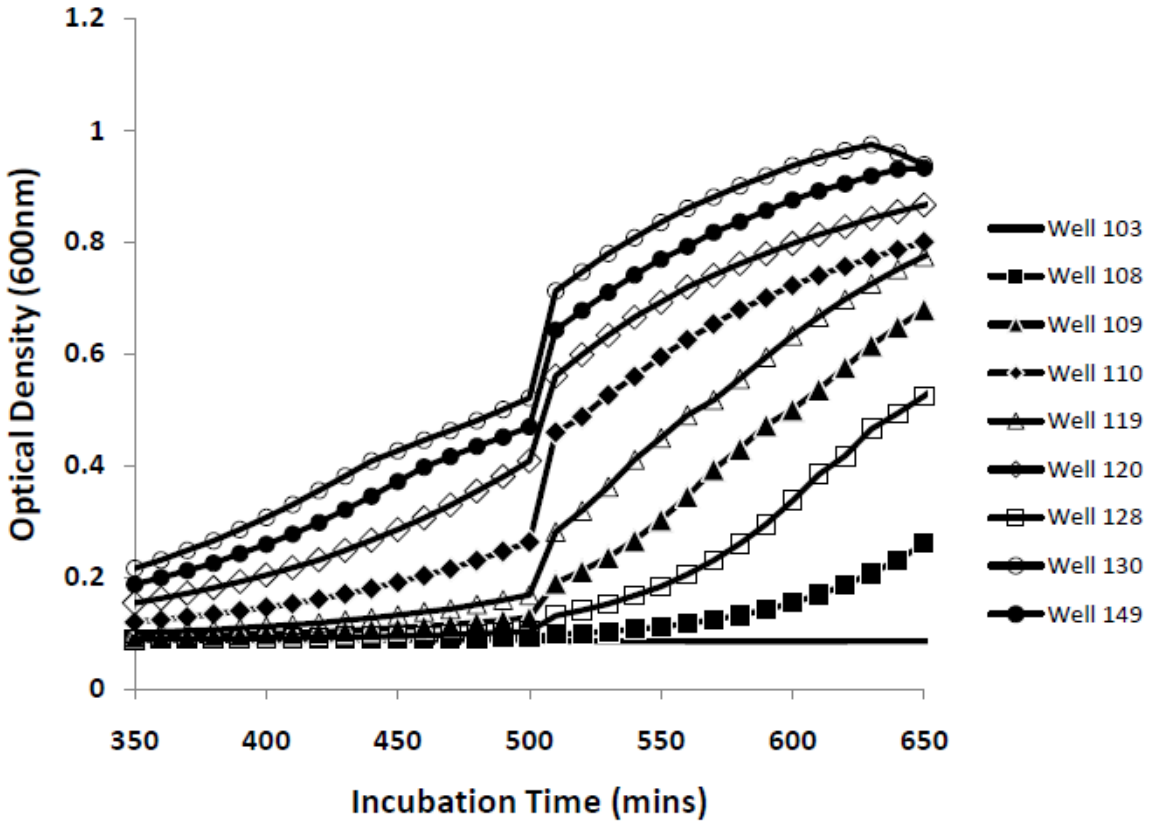


Figure4

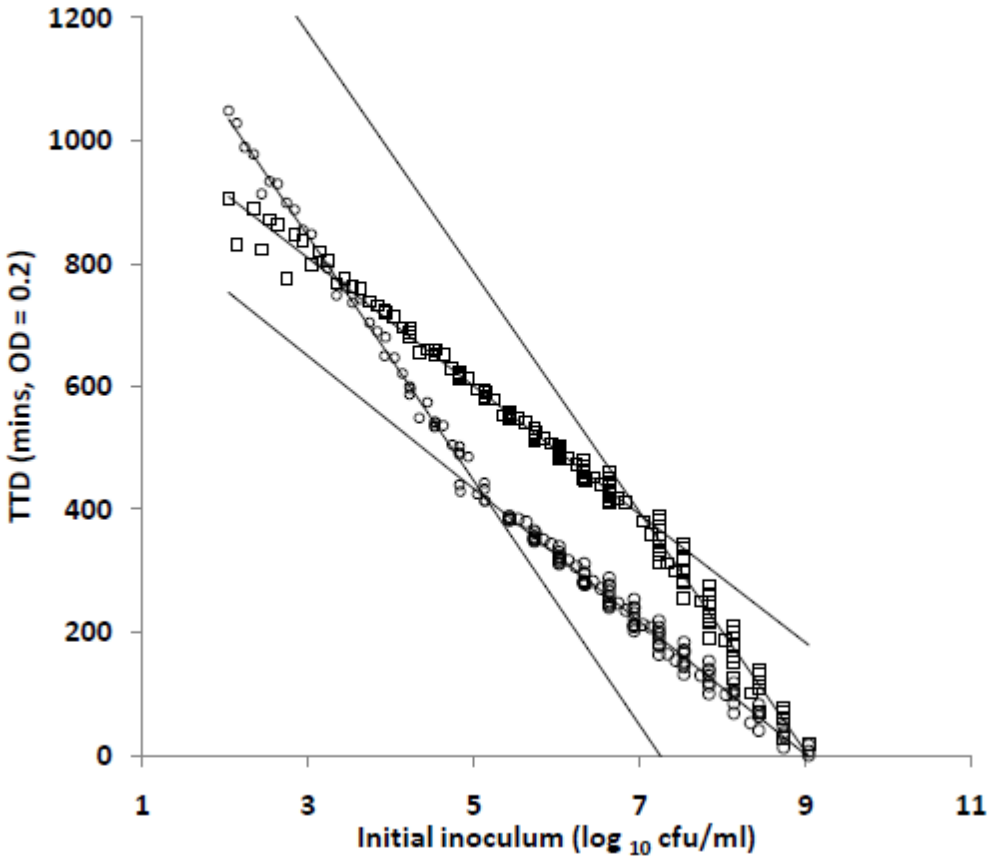


Figure5

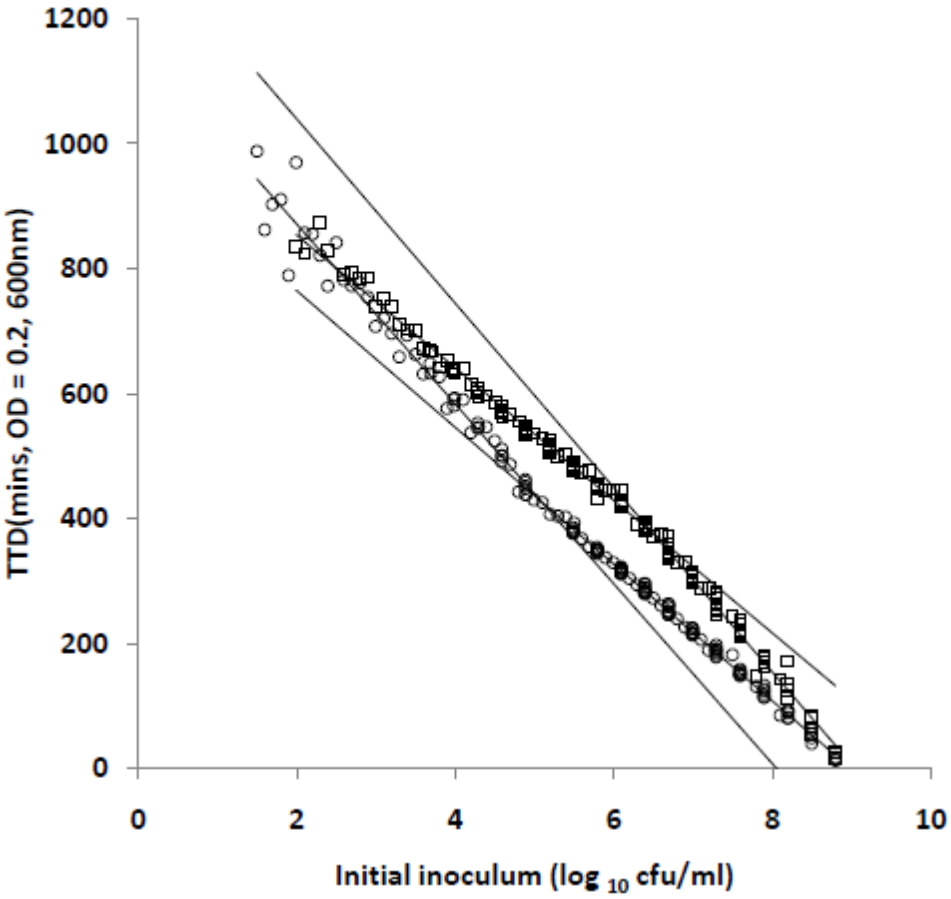


Figure6

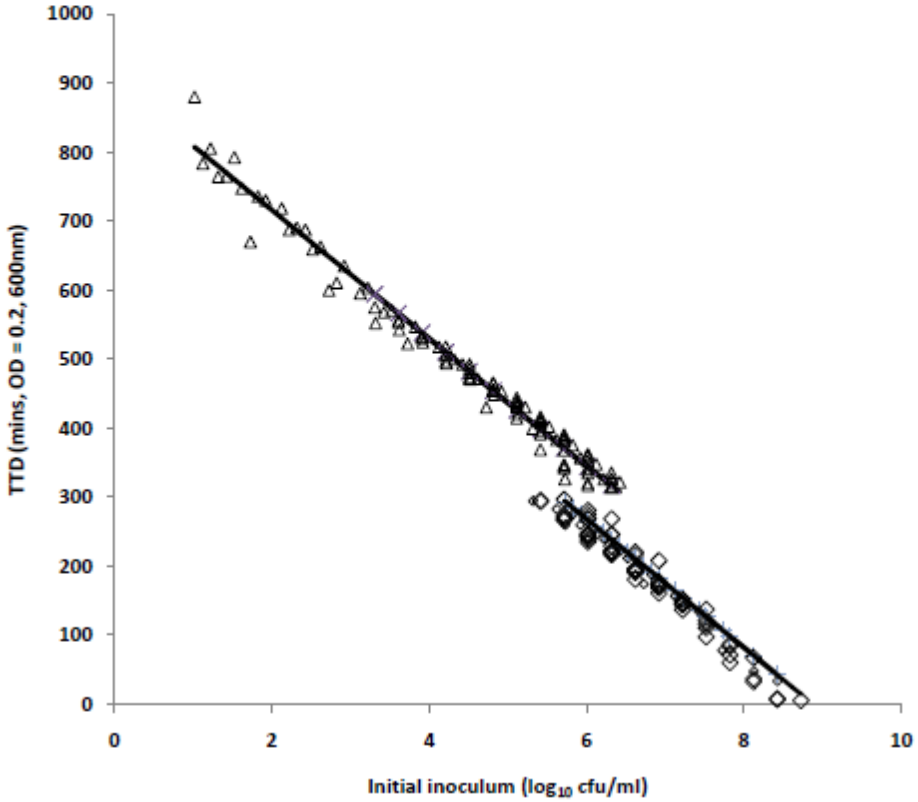


Figure7

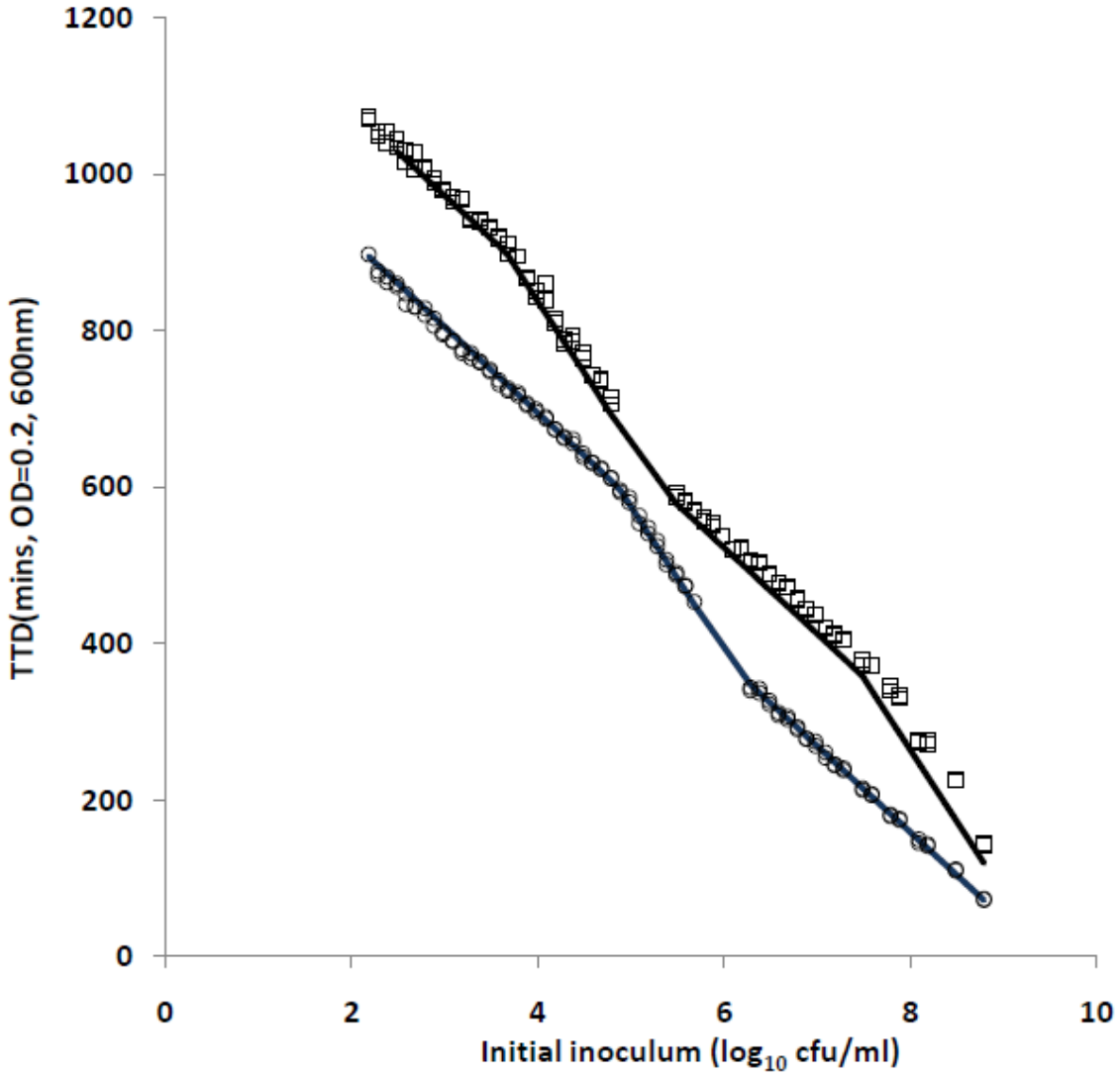
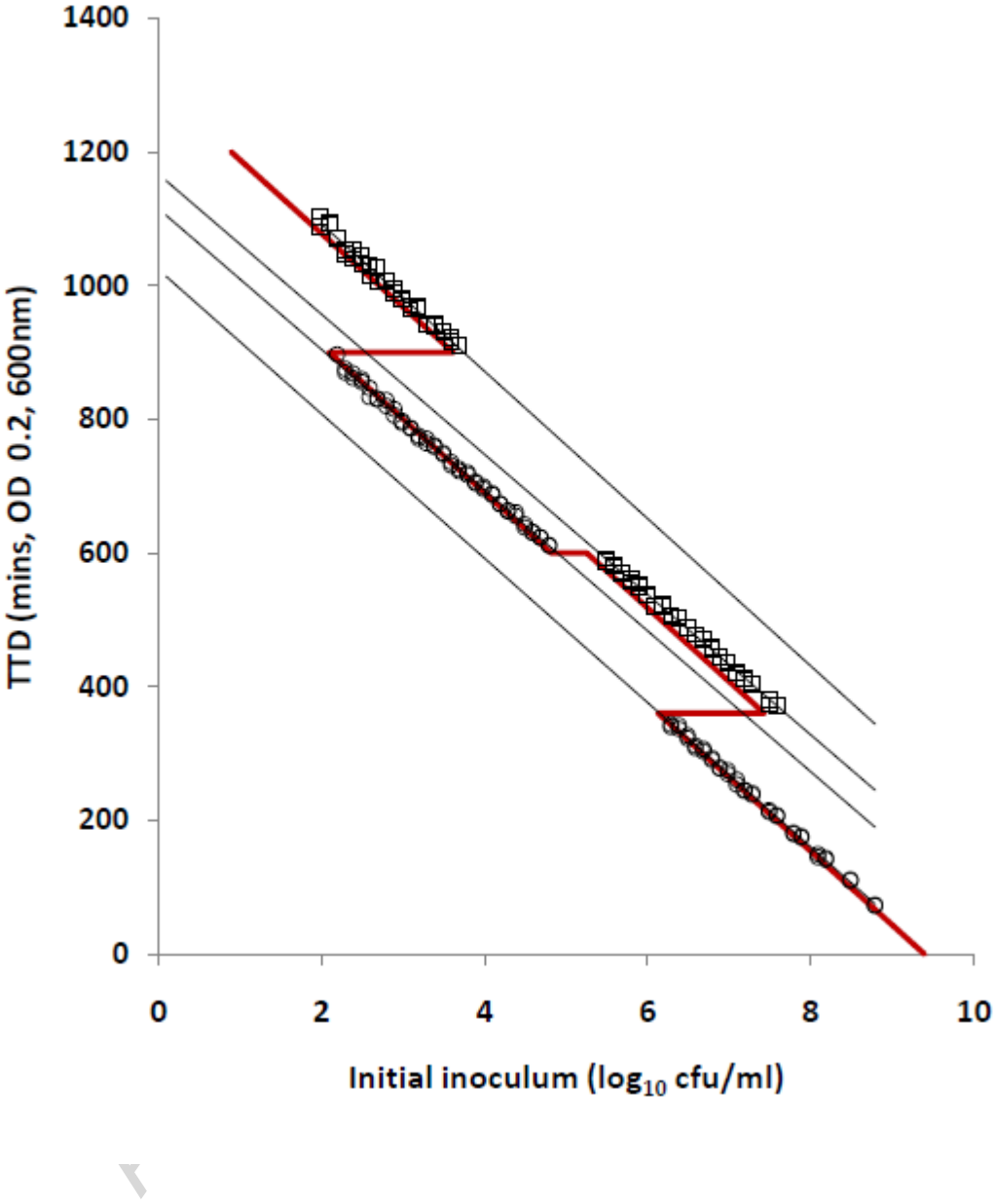


Figure8



Highlights

>Effect on growth rates of temperature jumps were monitored by optical density

> Data were modelled using the classical logistic equation.

> Growth rates changed to the new environmental conditions without lag induction.